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Report Title

ABSTRACT

The goal of the program was to develop atom + cavity QED systems capable of storing and coherently manipulating quantum information coded in long-lived ground states of trapped atoms. We have developed atom traps designed to trap arrays of atoms inside high-finesse optical resonators. We have incorporated these atom traps into our high-finesse optical resonators and distilled the number of atoms in the traps down to the single atom level. Our implementation will enable coherent quantum information processing between atomic qubits readily scalable to >20 qubits. The theoretical effort of this program focused on two goals: (1) exploring alternative strategies for atomic and optical-based systems capable of storing and manipulating quantum information, and (2) supporting the experimental program by providing detailed study of the laboratory systems.

List of papers submitted or published that acknowledge ARO support during this reporting period. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

1. Motional effects of trapped atomic or ionic qubits,. L. You, Phys Rev A 64, 012302 (2001).
2. Quantum correlations in two-boson wave functions, R. Paskauskas, and L. You, Phys Rev A 64, 042310 (2001).
3. Creating massive entanglement of Bose condensed atoms, K. Helmerson and L. You, Phys. Rev. Lett. 87, 170402 (2001).
4. All-optical formation of an atomic Bose-Einstein condensate, M.D. Barrett, J.A. Sauer, and M.S. Chapman, Phys Rev Lett. 87, 010404 (2001).
5. Storage ring for neutral atoms, J.A. Sauer, M.D. Barrett, and M.S. Chapman, Phys Rev Lett. 87, 270401 (2001).
6. Motional rotating wave approximation for harmonically trapped particles, O. Mustecapliuglu and L. You, Phys. Rev. A 65, 033412 (2002).
7. On the single mode approximation in spinor-1 atomic condensate, S. Yi, O. Mustecapliuglu, C. P. Sun, and L. You, Phys. Rev. A 66, 011601 (2002).
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14. Quantum logic between atoms inside a high Q optical cavity, L. You, X. X. Yi, and X. H. Su, Phys. Rev. A 67, 032308 (2003)
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16. Cavity QED with optically transported atoms, J. A. Sauer, K. M. Fortier, M. S. Chang, C. D. Hamley, and M. S. Chapman, Phys. Rev. A, 69, 051804(R) (2004).
17. Generating entangled photon pairs from a cavity-QED system, D. L. Zhou, B. Sun, C.P. Sun, et al., Phys. Rev. A, 72 (2005).
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19. Measuring the parity of an N-qubit state, B. Zeng, D.L. Zhou, L. You, Phys. Rev. Lett., 95, 110502, (2005).
20. Encoding a logical qubit into physical qubits, B. Zeng, D.L. Zhou, Z. Xu, et al., Phys. Rev. A, 71, 022309, (2005).
21. Nonadiabatic effects of atomic motion inside a high-Q optical cavity, P. Zhang, Y. Li, C.P. Sun, et al., Phys. Rev. A, 70, 063804, (2004).

Number of Papers published in peer-reviewed journals: 21.00

(b) Papers published in non-peer-reviewed journals or in conference proceedings (N/A for none)

Number of Papers published in non peer-reviewed journals: 0.00

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1. “Quantum Gases, Quantum Hoses and Quantum Cavities,” “Jorge Andre Swieca” Summer school on Quantum and Nonlinear Optics, Campinas, Brazil, January 2002.
2. “QUEST for all-optical BEC,” 32nd Winter Colloquium on the Physics of Quantum Electronics, Snowbird, UT, January 2002, (talk given by student M. Barrett).
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4. “All-Optical Bose-Einstein Condensates,” Quantum Electronics and Laser Optics Conference (QELS), Long Beach, CA, May 2002.
5. “All-Optical Bose-Einstein Condensates,” DAMOP Conference, Williamsburg, VA, June 2002.
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Number of Papers not Published: 20.00

(d) Manuscripts

Number of Manuscripts: 0.00

Number of Inventions:

Graduate Students

Murray Barrett (1.0)
Jake Sauer (1.0)
Ming-Shien Chang (1.0)
Kevin Fortier (1.0)
Mei Zhang (1.0)
Su Yi (1.0)
Xiaohua Su (1.0)
Michael Gibbons (0.0)
Soo Kim (0.0)
Sun Bo (0.5)

Number of Graduate Students supported: 10.00

Total number of FTE graduate students: 8.00

Names of Post Doctorates

O. Mustecaplioglu (0.5)
Xuexi Yi (0.5)

Number of Post Docs supported: 2.00

Total number of FTE Post Doctorates: 1.00

List of faculty supported by the grant that are National Academy Members

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Names of Faculty Supported

Michael S. Chapman
Li You

Number of Faculty: 2.00

Names of Under Graduate students supported

Shane Allman
Christopher Hamley
Anthony Mizzomori

Number of under graduate students: 3.00

Names of Personnel receiving masters degrees

Sally Maddox
David Zhu

Number of Masters Awarded: 2.00

Names of personnel receiving PHDs

Mei Zhang
Jacob Sauer
Su Yi

Number of PHDs awarded: 3.00

Names of other research staff

Sub Contractors (DD882)

Inventions (DD882)

Abstract

The goal of the program was to develop atom + cavity QED systems capable of storing and coherently manipulating quantum information coded in long-lived ground states of trapped atoms. We have developed atom traps designed to trap arrays of atoms inside high-finesse optical resonators. We have incorporated these atom traps into our high-finesse optical resonators and distilled the number of atoms in the traps down to the single atom level. Our implementation will enable coherent quantum information processing between atomic qubits readily scalable to >20 qubits. The theoretical effort of this program focused on two goals: (1) exploring alternative strategies for atomic and optical-based systems capable of storing and manipulating quantum information, and (2) supporting the experimental program by providing detailed study of the laboratory systems.

Publications

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1. "All-Optical Atomic Bose-Einstein Condensates", M.D Barrett, M.-S. Chang, C. Hamley, K. Fortier, J.A. Sauer and M.S. Chapman, to appear in the proceedings of the 18th International Conference on Atomic Physics, Cambridge, MA, July 28-August 2, 2002.

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20. "Quantum information with atoms, photons and ions," Gordon Conference on Atomic Physics, Tilton, NH, June 2005

Participating Scientific Personnel

Michael S. Chapman (PI)
Li You (co-PI)
Ozgur Mustecapliuglu (Post-doc)
Xuexi Yi (Post-doc)
Murray Barrett (Ph.D. student)
Jake Sauer (Ph.D. student)
Ming-Shien Chang (Ph. D. student)
Kevin Fortier (Ph. D. student)
Xiaohua Su
Mei Zhang (Ph. D. student)
Su Yi (Ph. D. student)
David Zhu (Master's student)
Sally Maddox (Master's student)
Anthony Mizumori (Undergraduate student)
Christopher Hamley (Undergraduate student)
Shane Allman (Undergraduate student)

Report of Inventions

none

Scientific Progress and Accomplishments

Findings

This joint experimental and theoretical project focused on quantum information processing (QIP) based on a cavity QED system with trapped *neutral* atoms. The principal scientific objectives were to integrate the underlying atom trap and cavity QED technologies and to distill traps down to the single atom level. As described below, we have successfully guided and transported atoms into our high-finesse optical cavities using a translating one-dimensional optical lattice, and we have observed the signals from single atoms as they are transported through the cavity.

Optical dipole force trap inside of cavity

Our strategy for creating a controllable neutral atom + cavity system is to employ an optical lattice trap loaded external to the cavity. By translation of the lattice achieved by changing the phase of the optical fields, the atoms can be controllably introduced into the cavity mode volume (see Fig. 1). The atom trapping capability and cavity fabrication aspects of system were developed during this project and considerable focus was placed on combining the two technologies, including incorporating the ability to translate the trap with respect to the cavity, ensuring UHV conditions, and minimizing length perturbations of the cavity caused by acoustic vibrations and uncontrolled temperature changes. In particular, keeping the high-finesse cavity on resonance requires the separation of the mirrors to be held to stabilities on the 10^{-11} m scale.

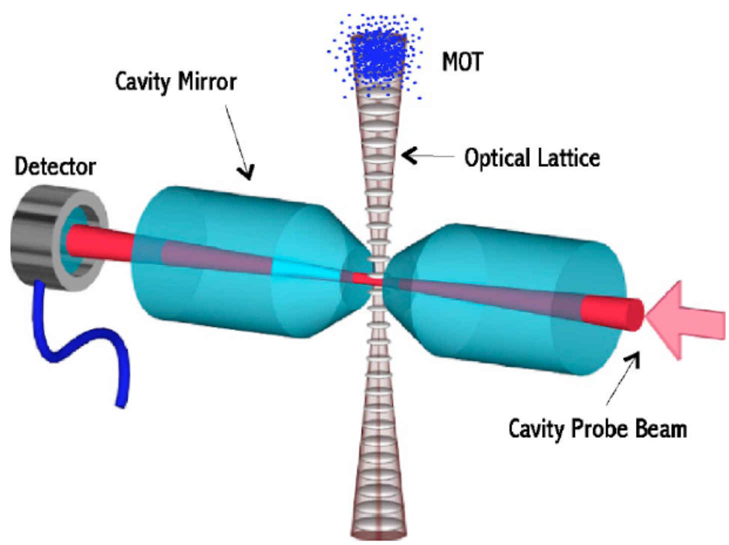


Fig 1: Two counter-propagating laser beams focused through the cavity in the vertical direction produce an optical lattice. Translating the lattice transports atoms collected in the magneto-optic trap (MOT) into the cavity mode below.

Our cavity design is a careful compromise allowing for significant vibration isolation and also small relative motion of the cavity and the trap laser beam. With this system, we have held the cavity on-resonance without any feedback for up to a minute—this corresponds to residual relative motion of the mirrors of 1 micron/year. This represents a significant improvement over previous microcavity systems, which require a fast bandwidth active feedback that can interfere with the atom + cavity system.

Initial experiments with trapped atoms

With the experimental system developed during this project, we have conducted a series of experiments. In our first experiment, we load atoms from a magneto-optic trap (MOT) into a single beam focus laser. This is shown schematically in Fig. 2 (left), which shows the focused laser beam intersecting the MOT and passing between the cavity mirrors. Once the MOT light is extinguished, the atoms are free to fall vertically under the force of gravity, while transversely they are guided into the cavity mode by the optical trap.

To observe the atoms passing through the cavity, we probe the cavity transmission with a weak laser field tuned to the atom and cavity resonance. In the strong coupling regime of our atom + cavity system, just a single atom interacts strongly enough with the cavity field to create a measurable change in the transmission of a weak cavity probe. Hence,

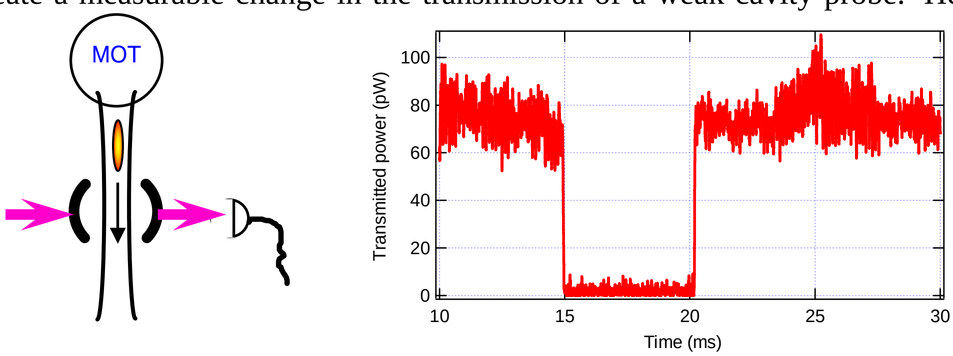


Fig 2. (Left) Atoms are transferred from the MOT to the focused laser trap. The atoms undergo freefall through the cavity, which is monitored by measuring the transmission of a weak probe beam. **(Right)** A typical trace showing the abrupt drop in transmission as the cloud of atoms passes through the cavity. The sharp drop in transmission is to the intrinsic optical bistability of the system.

we readily observe the passage of the guided atoms through the cavity mode as an abrupt drop in the cavity transmission (Fig. 2, right).

Indeed, the intrinsic non-linearity of the atom + cavity interaction is evident from the very sharp drop in transmission. The cavity transmission is shown in Fig. 3 as the atom cloud falls through the cavity for several different input powers. Although the atomic density time-profile through the cavity is approximately gaussian with a width (~ 1.5 ms FWHM) determined by the cloud temperature, the cavity transmission switches very abruptly and at different times for different powers. For the weakest probe powers, the individual atom transits are observed as spikes in the transmission at the leading and trailing edges of the cloud. The abrupt change in the cavity transmission is due to the absorptive optical bistability of the system resulting from the collective interaction of many radiating atoms with the cavity field.

To measure the bistability directly, we allow the atomic cloud to fall into the cavity with the probe beam off, then we quickly ramp the probe up to a high value and then down to zero again while the atoms are in the cavity. The results are shown in Fig 3., where the hysteresis is clearly evident in the 10-fold difference in the switching power. This data is taken from a single experimental run in real time.

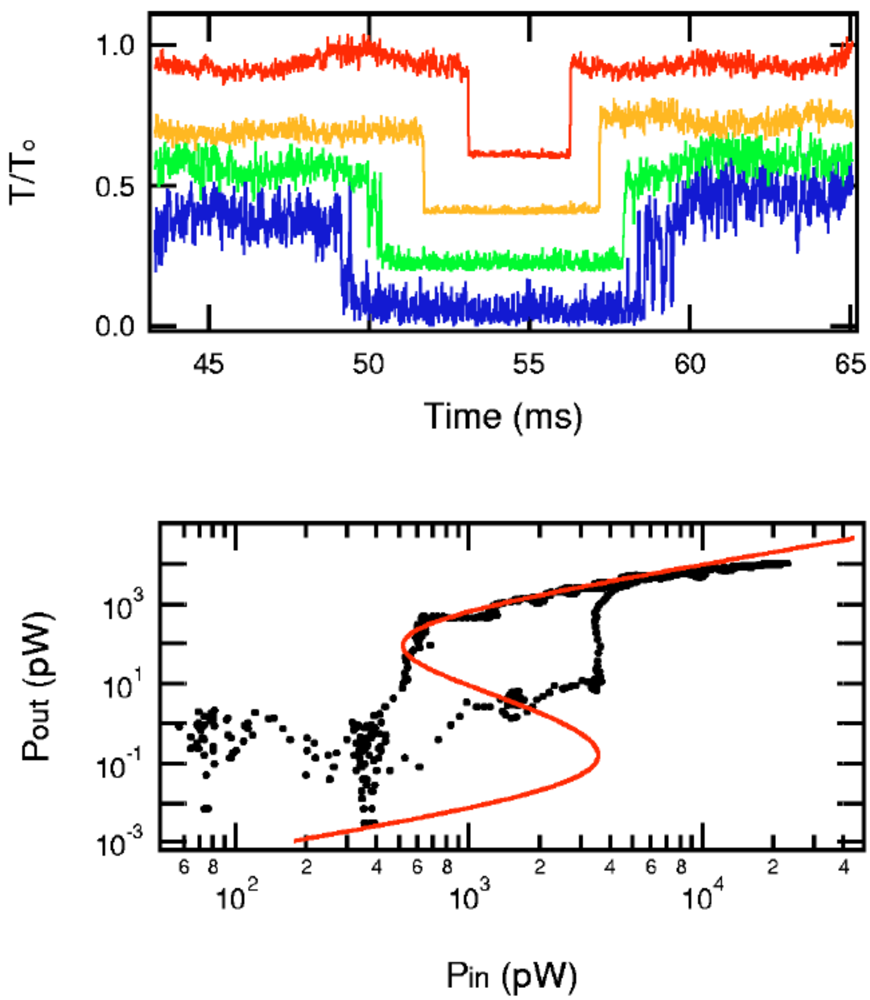


Fig. 3: The transmission of four different probe beam powers (2, 6.4, 20,30 pW from bottom to top) are plotted vs. time as the atomic cloud is guided though the cavity by the FORT beam. The graphs are offset by 0.25 each for clarity. (Bottom) A plot of cavity output power vs input power. The data was collected in 1 ms while the center of the atomic cloud overlapped with the cavity mode. The curve shows a theoretical plot of output vs. input power given by the optical bistability equation with a cooperativity C=200.

The intracavity atomic density at the instant when the cavity output power drops can be determined from the bistability equation. By increasing the probe power, we can map out the atom number vs. time. Fig. 4a shows data collected in this manner. Maximum intracavity atom numbers of ~100 and an atomic density ~10^{10} cm^{-3} inside the cavity were achieved. The maximum switched probe output power is 8 nW, corresponding to an intracavity intensity of 700,000 larger than the saturation intensity for the transition. It is remarkable that such a large intensity can be extinguished by only 100 atoms.

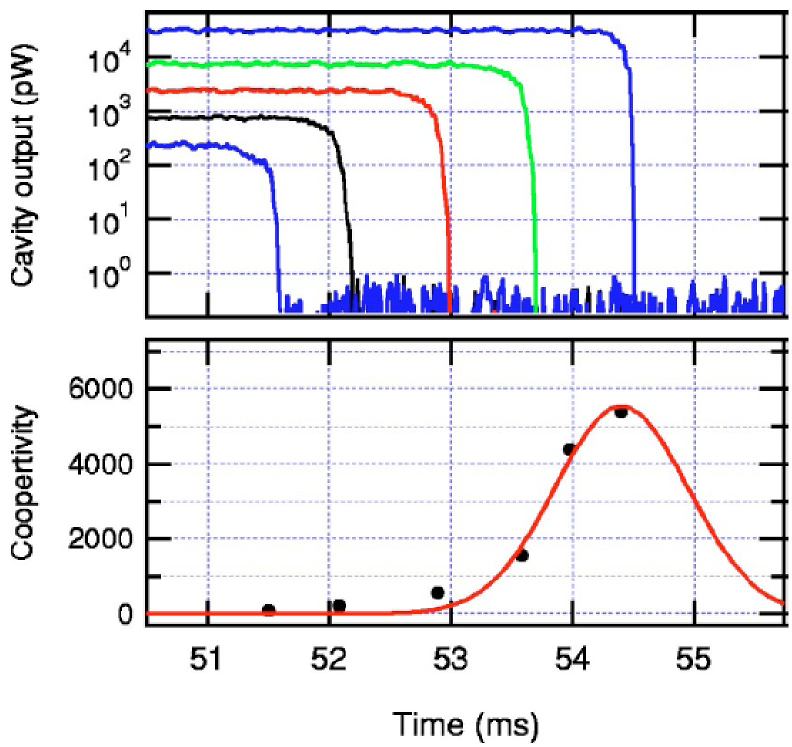


Fig 4: (Top) Data points from transmission curves of several different powers are fitted to bistability curves to extract cooperativity data. From left to right the curves show output power vs. cooperativity for input powers of 240, 758, 2400, 7580, and 31 200 pW. (Bottom) The atomic cooperativity vs. time is plotted as the atomic cloud falls through the cavity.

Translatable Lattice and Distillation to one atom

In our final experiment, we confine the atoms in a one-dimensional optical lattice generated by two counter-propagating laser beams. To transport the atoms into the cavity, the atoms are smoothly accelerated downward from rest through the cavity mode before coming momentarily to rest; then the lattice velocity is reversed to bring the atoms back up through the cavity a second time. The maximum velocity of the atoms 30 cm/s, and the maximum acceleration imparted is 1.5*g*. Images of the trapped atoms being lowered down into the cavity and then raised back up again are shown in Fig. 5.

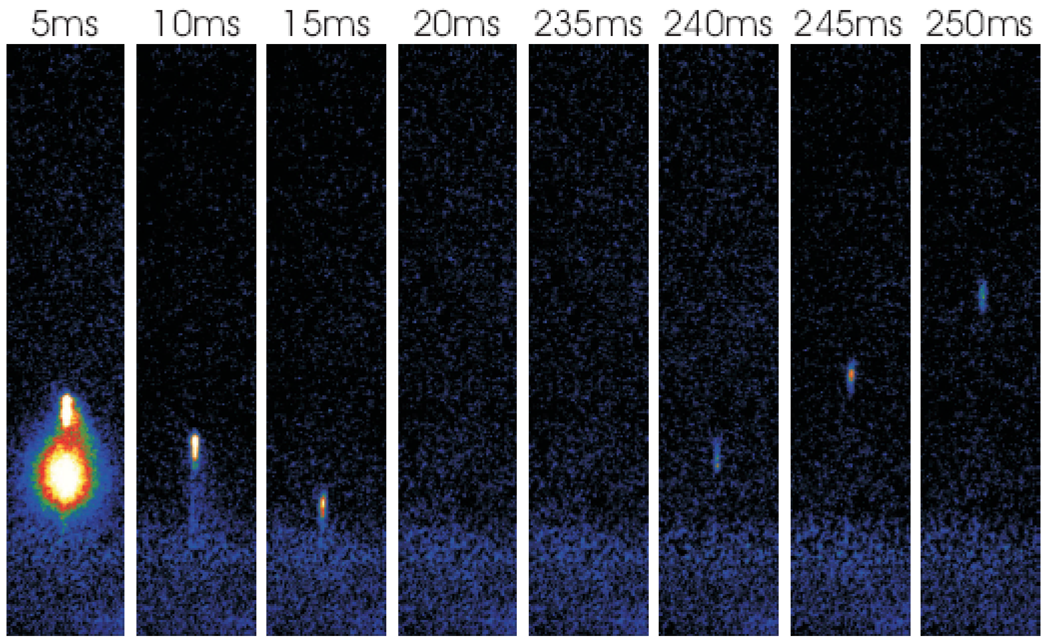
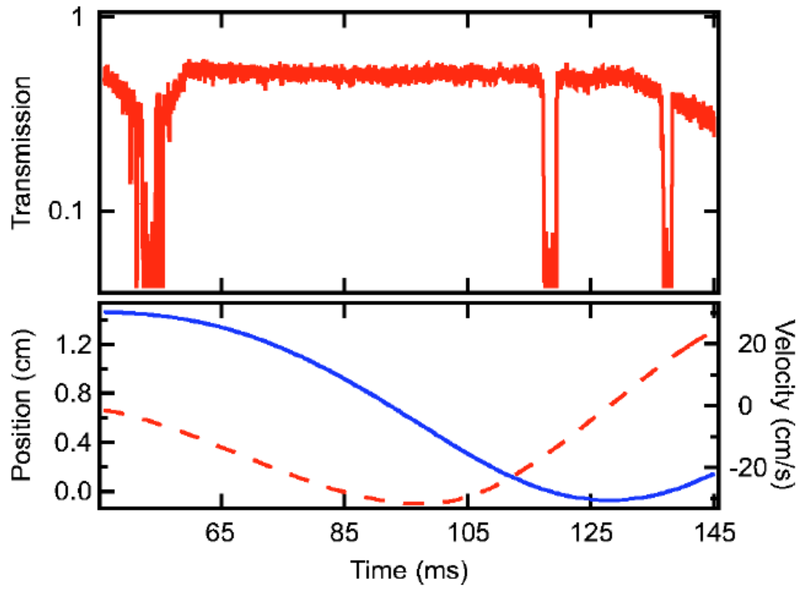


Fig 5: An image series of the atoms trapped in the optical lattice as they are lowered into the cavity and returned. In the first image, the unbound atomic cloud can be seen as it falls away from the trapped atoms in the lattice. Losses out of the lattice trap can be seen in the weak atomic signal of the last images.

The measured transmission through the cavity is shown for the lattice-transported atoms in Fig 6. The transmission drops at 150 ms and 170 ms show the atoms on their way down through the cavity and back up again. The first feature at 55 ms is due to atoms that are unbound at lattice sites, but still channeled through the cavity. The gradual drop in the baseline transmission for t > 125 ms is due to the cavity drifting out of resonance due to heating of the cavity mirrors caused by absorption of the lattice beams. The middle graph in Fig. 6 shows the position and velocity of the lattice sites measured relative to the cavity axis.

Because we are in the strong coupling cavity QED limit, our cavity is sensitive to single atoms within the mode. We can load very few atoms into our MOT by using low light levels and short loading times. Fig. 6 (bottom) shows a single atom traversing the cavity mode. This atom has been accelerated at ~30 m/s^2 and is delivered to the cavity 21 ms before gravity delivers the unbound atoms.



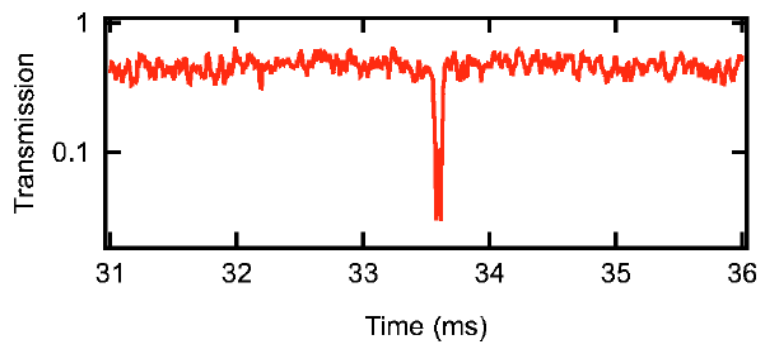


Fig 6: Transmission of the cavity probe beam shows a group of atoms transported first down and then back up through the cavity. The first dip in the transmission at 55 ms is due to unbound atoms as they fall through the cavity due to gravity. The second and third features are the trapped atoms moving down and up through the cavity (240 pW probe power). (Middle) Position (solid line) and velocity (dashed line) of the atoms trapped in the optical lattice. (Bottom) Delivery of a single atom into the cavity mode, arriving 21 ms before the free-falling atoms released from the MOT (2 pW probe power).

Improving the Lattice Trap

The atom trap lifetime in our initial experiments was ~100 ms, and this short lifetime limited our ability to controllably manipulate the atoms in the cavity. In the latter part of the grant period, we devoted considerable effort to investigate the reasons for the short lifetime. From these investigations, we determined that the trap lifetime was initially limited by the amplified spontaneous emission (ASE) of the near-resonant (782-784 nm) diode lasers that we were using for the lattice beams. This problem was alleviated by moving to larger detuning (850 nm) which we did using both amplified diode lasers and an Argon-ion pumped Ti:Sapphire laser. We also determined that our ability to manipulate the atoms in the translating lattice beams depended critically on the spatial and temporal quality of the lattice formed by the interfering counter-propagating trap beams.

As a result of this work, we now have a trap lifetime in the lattice of many seconds, and the lattice quality is now such that we can execute multiple translations of the atoms. The longer lifetime is shown in Fig. 7. These data were taken with the amplified diode laser system at 850 nm. The lattice lifetime is still shorter than the lifetime with just a single focused traveling wave laser beam possibly due to technical noise on the acousto-optic modulators used to generate the standing wave beams. Although this could be improved with higher quality frequency sources, it does not pose a current limitation on our experiments.

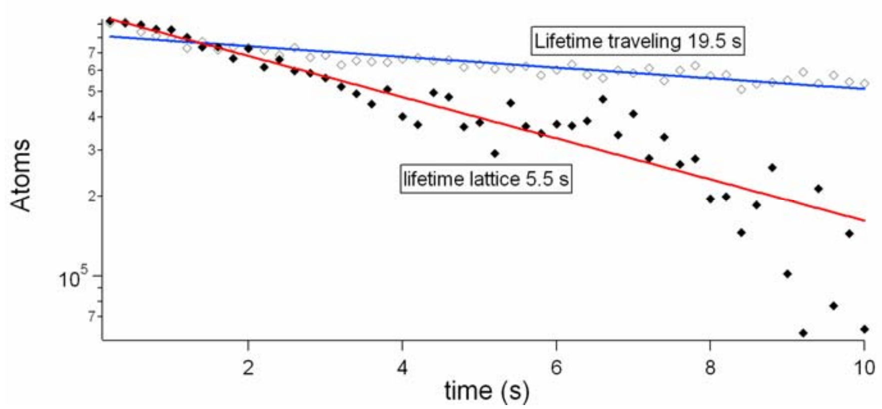


Fig 7: Lifetime of the trapped atoms in both a single focus trap and a standing wave lattice trap. The trap laser in both cases is a single frequency amplified diode laser system at 850 nm. The lifetime of the traveling wave trap is limited by collisions with thermal atoms in the residual vacuum.

The improved ability to manipulate the atoms in the moving lattice trap is shown in Fig. 8. This figure shows atoms being repeated transported over 3 mm with little loss.

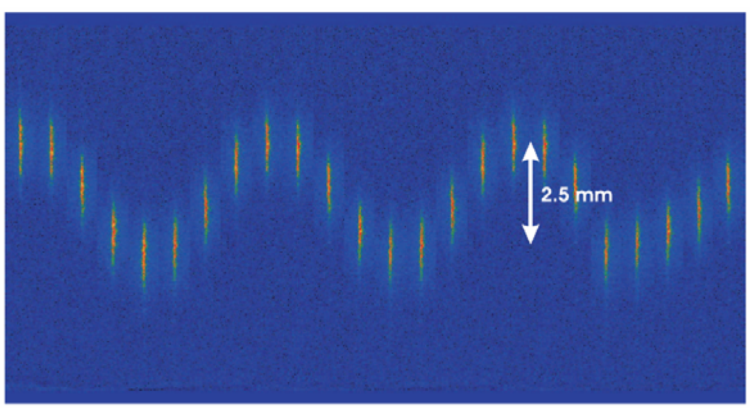


Fig 8: An image series shows many oscillations of the atoms in the optical conveyor. There is a 1 ms delay between each image.

We have also studied our ability to transport the atoms over longer distances. This is shown in Fig. 9. We can transport the atoms with little loss up to about 6 mm. This corresponds to a movement of over 10^4 lattice sites and indicates the high quality of the standing wave.

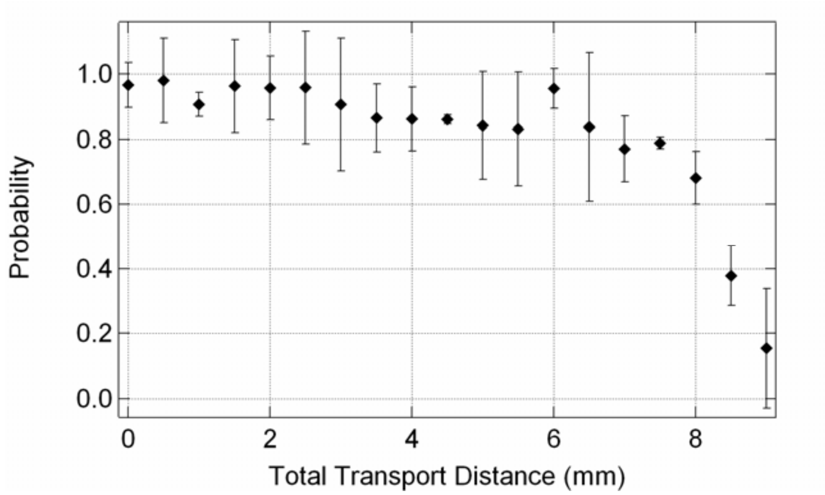


Fig 9: Probability to transport over a specified distance. Here, we transport the atomic cloud a known distance, return it to its original location and image the remaining atoms in the cloud.

Summary and future directions

In conclusion, we have realized a cavity QED system with optically trapped and transported atoms. This system provides means to controllably introduce atoms in and out the cavity mode. In our initial experiments, our ability to manipulate the atoms in the lattice is limited by the lifetime of our lattice trap. During the course of this grant period, we have dramatically improved this aspect of our experiment. We are encouraged by our progress in this effort, and anticipate that this system will provide a valuable tool for quantum information science in the future.

Technology Transfer

None